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Estimation of Optimal Biomass Removal Rate Based on Tolerable Soil Erosion for Single-Pass Crop Grain and Biomass Harvesting System

M. Karkee, R. P. McNaull, S. J. Birrell, B. L. Steward

Abstract. *As the demand for biomass feedstocks grows, it is likely that agricultural residue will be removed in a way that compromises soil sustainability due to increased soil erosion, depletion of organic matter, and deterioration of soil physical characteristics. Since soil erosion from agricultural fields depends on several factors including soil type, field terrain, and cropping practices, the amount of biomass that can be removed while maintaining soil tilth varies substantially over space and time. The RUSLE2 soil erosion model, which takes into account these spatio-temporal variations, was used to estimate tolerable agricultural biomass removal rates at field scales for a single-pass crop grain and biomass harvesting system. Soil type, field topography, climate data, management practices, and conservation practices were stored in individual databases on a state or county basis. Geographic position of the field was used as a spatial key to access the databases to select site-specific information such as soil, topography, and management related parameters. These parameters along with actual grain yield were provided as inputs to the RUSLE2 model to calculate yearly soil loss per unit area of the field. An iterative technique was then used to determine site-specific tolerable biomass removal rates that keep the soil loss below the soil loss thresholds (T) of the field. The tolerable removal rates varied substantially with field terrain, crop management practices, and soil type. At a location in a field in Winnebago county, Iowa, with ~1% slope and conventional tillage practices, up to 98% of the 11 Mg ha^{-1} total above-ground biomass was available for collection with negligible soil loss. There was no biomass available to remove with conventional tillage practices on steep slopes, as in a field in Crawford county, Iowa, with a 12.6% slope. If no-till crop practices were adopted, up to 70% of the total above-ground biomass could be collected at the same location with 12.6% slope. In the case of a soybean-corn rotation with no-till practices, about 98% of total biomass was available for removal at the locations in the Winnebago field with low slopes, whereas 77% of total biomass was available at a location in the Crawford field with a 7.5% slope. Tolerable removal rates varied substantially over an agricultural field, which showed the importance of site-specific removal rate estimation. These removal rates can be useful in developing recommended rates for producers to use during a single-pass crop grain and biomass harvesting operation. However, this study only considered the soil erosion tolerance level in estimating biomass removal rates. Before providing the final recommendation to end users, further investigations will be necessary to study the potential effects of continuous biomass removal on organic matter content and other biophysical properties of the soil.*

Keywords. *Biomass feedstock, Biomass harvesting, Corn stover, Rainfall erosion, Soil loss, Variable-rate removal.*

One of the most critical challenges the world is facing today is the increasing demand for energy. To minimize adverse effects on the environment and dependence on non-renewable fossil fuels, renewable energy sources must be explored and expanded in every possible dimension (Glassner et al., 1999). Studies have shown that cellulosic biomass could be one important and significant source for biofuel and other bioenergy generation. Researchers are developing and improving technologies and infrastructure for fuel production from cellulosic biomass (Hettenhaus et al. 2000). The U.S. Department of Energy (USDOE, 2007) has set a goal to replace 30% of fossil fuels with biofuels by the year 2030. One billion dry tons of biomass feedstock is necessary to meet this goal, which will not be possible without extensive use of various types of cellulosic biomass (Perlac et al., 2005). In recent years, energy crops, forest biomass, and agricultural residue have been widely studied as viable sources of cellulosic biomass (Wilhelm et al., 2004; Andrews, 2006). Corn stover has been the primary focus among these sources because of its availability in large quantities and at relatively low costs (DiPardo, 2000; Allmaras et al., 2000; Wilhelm et al., 2004; Blanco-Canqui, 2010). Consequently, agricultural biomass such as corn stover has been and will be collected at a steadily increasing rate to meet the increasing demand for biomass feedstocks in the short to medium term.

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However, excessive removal of agricultural biomass from agricultural fields may have adverse effects on soil quality and the environment. Soil structure, soil organic matter (SOM) content, soil organic carbon (SOC) sequestration, nutrient cycling, and soil biodiversity can be affected if crop biomass is removed without considering long-term sustainability (Karlen et al., 1994; Andrews, 2006; Blanco-Canqui, 2010). Crop and biomass yield may decrease in the long run with excessive and continuous biomass removal due to increased erosion, reduced SOM and nutrients, and lowered biodiversity (Andrews, 2006). Therefore, it is necessary to optimize agricultural residue removal rates so that degradation of soil and the environment is prevented and agricultural production can be sustained.

To ensure sustainability of agricultural production systems, only a certain proportion of biomass can be removed from agricultural fields. The actual removable amounts depend on various parameters related to the agricultural field, cropping system, and environment. Some of the important parameters dictating the amount of agricultural biomass that can be removed safely include soil type and condition, crop type and crop rotation, tillage practices, climate, field topography, and the extent of field surface covered by agricultural residue (Benoit and Lindstorm, 1987; Reicosky et al., 1995; Dick et al., 1998; Linden et al., 2000; Nelson, 2002; Wilhelm et al., 2004; Wilson et al., 2004). Potter et al. (1998) compared the effects on soil quality due to biomass removal in various climatic conditions and found that climatic conditions interact strongly with the tolerable biomass removal rates. Field topography is another important factor, as the level of soil erosion depends heavily on slope and slope length. Andrews (2006) recommended the use of tools such as the Revised Universal Soil Loss Equation (RUSLE), the Wind Erosion Equation (WEQ), and the soil conditioning index to estimate sustainable crop residue removal rates, which take into account factors such as soil type, terrain, management practices, and yield. For a given geographic location in a field with all other variables being fixed, soil loss due to erosion will depend primarily on the amount of agricultural biomass removed from the field. However, the effect of residue removal from agricultural fields will be more adverse in conventional tillage systems, which suggests a strong interaction between tillage and the amount of biomass that can be removed safely (Linden et al., 2000; Wilson et al., 2004).

Based on the rate and role of topsoil formation, USDA-NRCS has recommended a tolerable soil loss threshold (T) for soils across the U.S. This threshold can be viewed as the tolerable soil loss for sustainable agricultural production (Nelson, 2002). If a field experiences soil loss above this threshold, the overall soil quality will decline over time, and agricultural production will not be sustainable. Some researchers have estimated tolerable agricultural biomass removal rates for different types of crops in various U.S. states based on the soil loss threshold. Nelson (2002) used tolerable soil loss due to rain and wind erosion to calculate recommended corn stover and wheat straw removal rates for 37 U.S. states. Nelson et al. (2004) performed similar studies for corn and wheat straw in the ten largest corn producing states in the Midwestern U.S.; RUSLE was used as the water erosion model. In these studies, county-level average removal rates were determined, and a 20% general biomass removal rate was recommended. McAloon et al. (2000) suggested an average corn stover removal rate of 30%, and Hettenhaus et al. (2000) suggested an average rate of 50% to 60% for sustainable agricultural production in the Corn Belt. Sheehan et al. (2004) applied the methodology of Nelson (2002) in 99 counties in Iowa and suggested that about 40% of the residue can be collected from Iowa corn fields under reduced/mulch tillage while keeping the soil erosion at or below the tolerable level. The sustainable removal rate increased to 70% for no-till conditions. The study made the assumption that all farmers will implement continuous corn rotation. Johnson et al. (2006) estimated that 50% to 60% of the biomass can be removed from corn fields assuming that reduced tillage is used.

These studies suggest that there exists a substantial proportion of agricultural biomass such as corn stover and wheat straw that can be removed while keeping soil erosion and soil organic matter loss within tolerable limits. The amount that can be removed safely varies from 0% to 100% over space and time within a field depending on various parameters such as soil type, crop management practices, topography, climate, and yield (Nelson et al., 2004; Newman et al., 2010). General guidelines for agricultural biomass removal practices can be formulated based on these studies. However, none of these studies incorporated in-field variability into recommended biomass removal rates. County-level average removal rates estimated by these studies may not be useful for in-field optimization of biomass collection rates. It is necessary to develop site-specific harvest guidelines that can adapt to changing parameters within a field during harvesting operations so that a sustainable use of agricultural biomass can be ensured (Wilhelm et al., 2004; Andrews, 2006). The objective of this work was to study in-field variability of removable agricultural biomass for developing a decision method to vary the percentage of biomass collected in a field by a single-pass harvesting system. The RUSLE2 model was used to estimate tolerable biomass removal rates based on site-specific parameters such as management practices, field topography, soil type, conservation practices, crop yield, and climate.

Methods

A methodology developed to estimate site-specific tolerable biomass removal rates is described in this section. In this article, “biomass removal rate” refers to the percentage of the total above-ground agricultural biomass that will be available for collection during single-pass grain and biomass harvesting. The methodology was used (1) to calculate tolerable biomass removal rates at several geographic locations in two different agricultural fields in Iowa and (2) to develop a variable-rate biomass collection map for one of the two fields. This methodology considered only soil erosion and no other factors such as SOM and soil biophysical characteristics in assessing biomass removal rates. The RUSLE2 erosion model can be used to estimate the biomass removal rate so that soil erosion from agricultural fields does not exceed soil loss thresholds (T). Biomass removal rates estimated based on the water or rain erosion tolerance will be reasonable in the fields in Iowa where wind erosion is not substantial. However, these removal rates will have to be treated carefully. Even though the soil loss is tolerable, loss of SOM may be significant, particularly in flat fields where removal of a high percentage of above-ground biomass is suggested based on the erosion model results. Before providing recommended removal rates to farmers, these rates should be adjusted based on the analysis of the effect of continuous biomass removal on SOM content.

RUSLE2 Water-Induced Soil Erosion Model

The Revised Universal Soil Loss Equation (RUSLE) is a semi-empirical water-induced soil loss prediction model developed based on the Universal Soil Loss Equation (USLE). RUSLE is a widely used soil loss model for comparing conservation practices. The USDA Natural Resource Conservation Service (NRCS) uses RUSLE to review conservation compliance in various agricultural and conservation programs. NRCS also suggests the use of RUSLE to estimate the tolerable biomass removal rate from agricultural fields. The basic RUSLE model is represented by:

$$A = r*k*l*S*c*p \tag{1}$$

where A is the average annual soil loss, r is the erosivity factor, k is the soil erodibility factor, l is the soil slope length factor, S is the slope factor, c is the cover management factor, and p is the supporting practices factor.

Based on the RUSLE model, soil erosion prediction software called RUSLE2 was developed. RUSLE2 provides a user-friendly graphical user interface for providing inputs to and extracting outputs from the model (table 1). The primary output of the model is soil loss for conservation planning (called "soil loss" in this article). This output represents the net amount of soil loss that occurs per unit area of field within a year. RUSLE2 takes sediment deposits into account when calculating the soil loss. RUSLE2 also provides the soil conditioning index, surface residue cover, soil loss from erosion, and sediment delivery as additional outputs. The soil conditioning index depicts how well soil organic matter will be maintained in the field. Surface residue cover represents the amount of biomass left on the ground plus external materials added to the ground such as straw mulch and manure. Soil loss from erosion represents the average soil loss over the slope where detachment occurs. Sediment delivery is the amount of sediment delivered to outlets at the edges of a field. The RUSLE2 team has also developed and distributed a collection of dynamically linked RUSLE2 libraries called RomeDLL. RomeDLL was incorporated into an application in this study to estimate site-specific tolerable biomass removal rates.

Parameter Estimation

Input parameters required to run the erosion model were acquired using public domain data. Management practices were based on common practices of Iowa farmers and were implemented with RUSLE2 using operations defined in the crop management database. Two crop management practices, conventional tillage and no-till, were used in the analysis (table 2). Field operations for these management practices were defined based on the recommendations of Nelson (2002), Nelson et al. (2004), Newman et al. (2010), and RUSLE2 crop management templates (RUSLE2, 2003). Crop rotations used in the analysis included single-year corn and two-year soybean-corn rotations. It was important to analyze continuous corn rotation with no-till as that is a likely future practice to meet the demand for cellulosic biomass.

Table 1. Inputs and outputs of RUSLE2.

Inputs	Outputs
Management practices	Soil loss
Soil data	Soil loss threshold
Slope and slope length	Surface cover due to residue
Climate data	Sediment delivery
Crop grain yield	Soil conditioning index
Supporting practices	

County-level soil databases were available for download from the RUSLE2 homepage and were used in this work. Soil type was used by RomeDLL to access the database for the required soil type and its attributes. Spatial soil type maps were downloaded in the ArcView shapefile format (ESRI, Inc., Redlands, Cal.) from the USDA-NRCS and were used to determine the soil type at particular locations (fig. 1). Soil attributes associated with each soil type in a soil polygon (vector) map (an example is represented in fig. 1 by the arrow from the soil polygon map to the attribute table) were used to covert soil polygon maps into 10 m resolution raster maps representing soil type identifiers (Soil ID) in a gridded form. A resolution of 10 m was selected for the soil map to make the dataset consistent with the digital elevation models (DEMs) used in this study. During polygon to raster conversion, if two or more soil types were present within a single cell, the soil type covering the maximum area within the cell was selected. This raster map was used to access the soil type ID corresponding to a geographic location defined by the latitude and longitude of that location. The soil type ID was then used to search for the corresponding soil type in the RUSLE2 database. The soil type was then used as an input to the RUSLE2 model.

Slope and slope length at the corresponding location were calculated using a 10 m resolution DEM of the field. DEMs with a 10 m resolution were used in this study assuming that this resolution will be sufficient to represent the topography of a row-crop agricultural field. This dataset was selected also because it was available publicly in the U.S.; DEMs for

Table 2. Field operations for conventional tillage and no-till management practices. These operations were used in RomeDLL to estimate soil loss for various combinations of crop rotations and field operations in two different fields in Iowa.

	Corn		Soybean	
Management	Date	Operation	Date	Operation
Conventional tillage	25 April	Moldboard plow	11 May	Moldboard plow
	10 May	Field cultivator, 15 to 30 cm sweeps	26 May	Tandem disk, secondary operation
	15 May	Tandem disk, secondary operation	31 May	Tandem disk, light finishing
	17 May	Tandem disk, secondary operation	3 June	Field cultivator, 15 to 30 cm sweeps
	20 May	Planter, double-disk opener with fluted coulter	5 June	Planter, double disk opener with fluted coulter
	25 Oct.	Harvest	30 Oct.	Harvest
No till	20 May	Planter, double-disk opener with fluted coulter	5 June	Drill or air seeder, single-disk opener, 17.5 to 25 cm spacing
	25 Oct.	Harvest	30 Oct.	Harvest

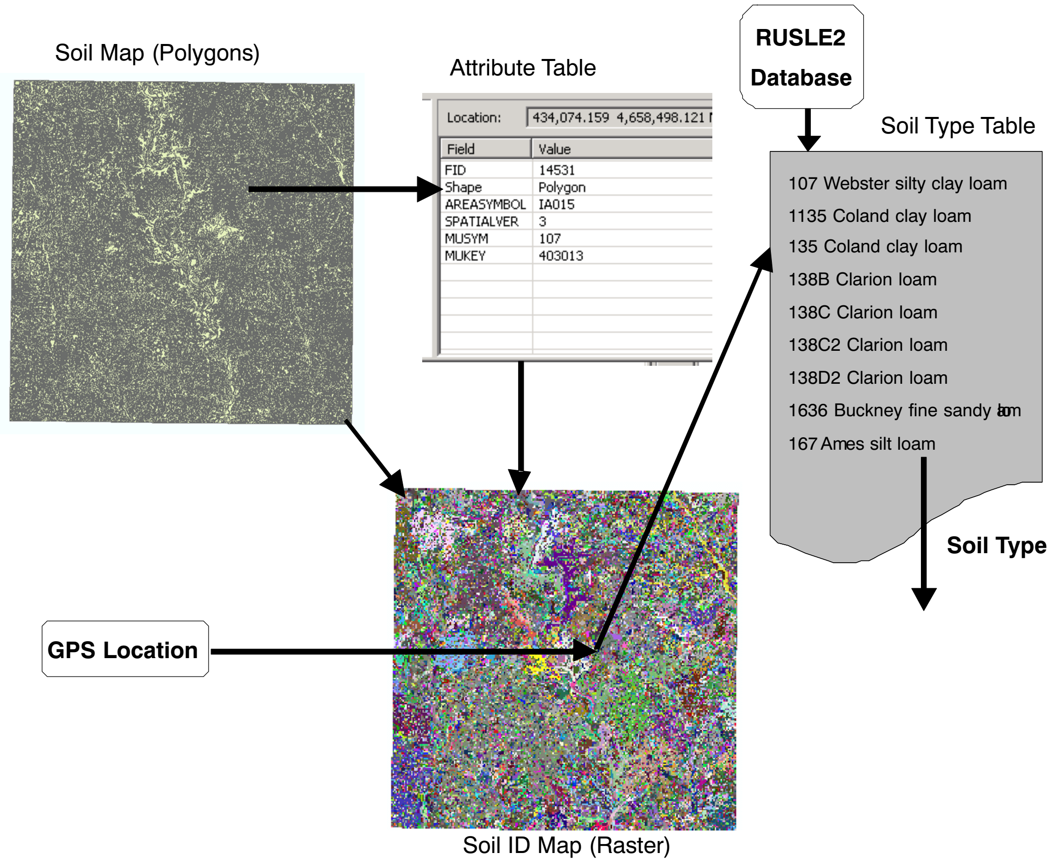

Figure 1. Determining the soil type at a geographic location using soil polygon map, attribute table, and soil type list available in the RUSLE2 soil database. Each polygon in the soil polygon map was associated with an attribute table. The soil polygon map and the attribute table were used to generate a raster map, which was then used to find the soil type at a given geographic location.

the whole U.S. were acquired through the U.S. Geological Survey (USGS). Slopes in east-west and north-south directions were combined to calculate the resultant slope at each geographic location. A program implemented by the Geographic Resources Analysis Support System (GRASS) GIS software (The Open Source Geospatial Foundation, Vancouver, British Columbia, Canada), which was publicly available for download, was modified and used in this study to calculate the slope length parameter.

Climatic data specific to counties were also retrieved from the databases downloaded with the RUSLE2 software and RomeDLL. County-level average yields provided by the USDA National Agricultural Statistics Service (USDA-NASS, 2010) were used in this study as the input yield to the model. It was assumed that the crop rows were parallel to the contour lines in the field by selecting the appropriate supporting practice. It was also assumed that there were no other supporting practices such as strips, barriers, diversions, terraces, sediment basins, or subsurface drainage implemented in the field.

Calculating Tolerable Biomass Removal Rates

RUSLE2 was used to calculate soil losses and tolerable biomass removal rates at six different geographic locations in two different fields in Iowa with site-specific inputs and specific amounts of agricultural residue left in the field. The method was also used to develop a variable-rate biomass collection map for one of the two fields. The intent was to use this approach to control a single-pass harvester for variable-rate biomass collection. However, the RUSLE2 database did not include single-pass grain and biomass harvesting operations. Therefore, four different combinations of standard harvest types, shredding operations, and baling operations were used to vary the amount of biomass removed from the field, thus varying the level of surface cover due to residue. The combinations used in this process were: (1) harvesting with 50% standing stubble (no biomass was collected), (2) harvesting with 30% standing stubble plus straw or residue baling (about 25% of above-ground biomass was collected), (3) harvesting with 20% standing stubble plus stalk strips and residue baling (about 75% collection), and (4) same as combination 3 plus one more pass of residue baling (about 100% collection). RUSLE2 calculated the soil loss iteratively with different amounts of surface cover in each iteration starting with the first combination, in which all of the biomass was left on the ground (fig. 2). The total amount of above-ground biomass yield was also calculated by RUSLE2 based on the crop yield data (Pordesimo et al., 2004). The difference between the total biomass available in the field and the amount of biomass left for field surface cover was calculated as the removal rate. The iterative process was continued to get the removal rates very close to the level (above and below) that caused soil losses very close to the threshold (*T*). Linear interpolation was then applied to estimate the biomass removal rate that caused a soil loss equal to the soil loss threshold. A RomeDLL-based application was developed in Visual C++ (Microsoft Corp., Redmond, Wash.) to perform this iterative process of estimating tolerable biomass removal rates.

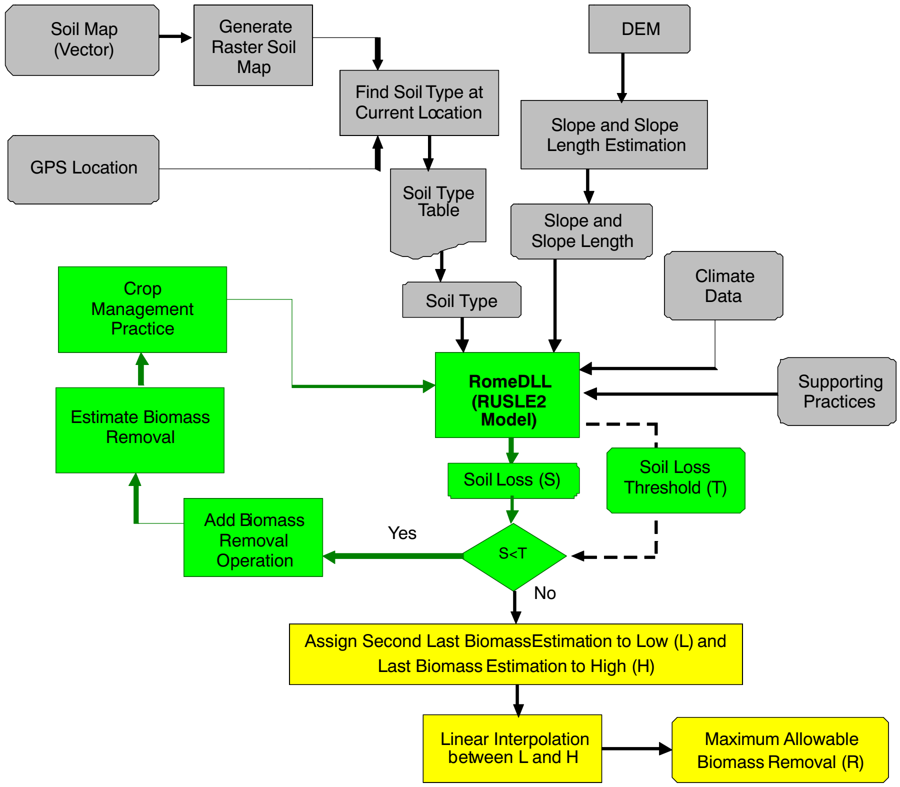

Figure 2. Process and data flowchart for tolerable biomass removal rate calculation.

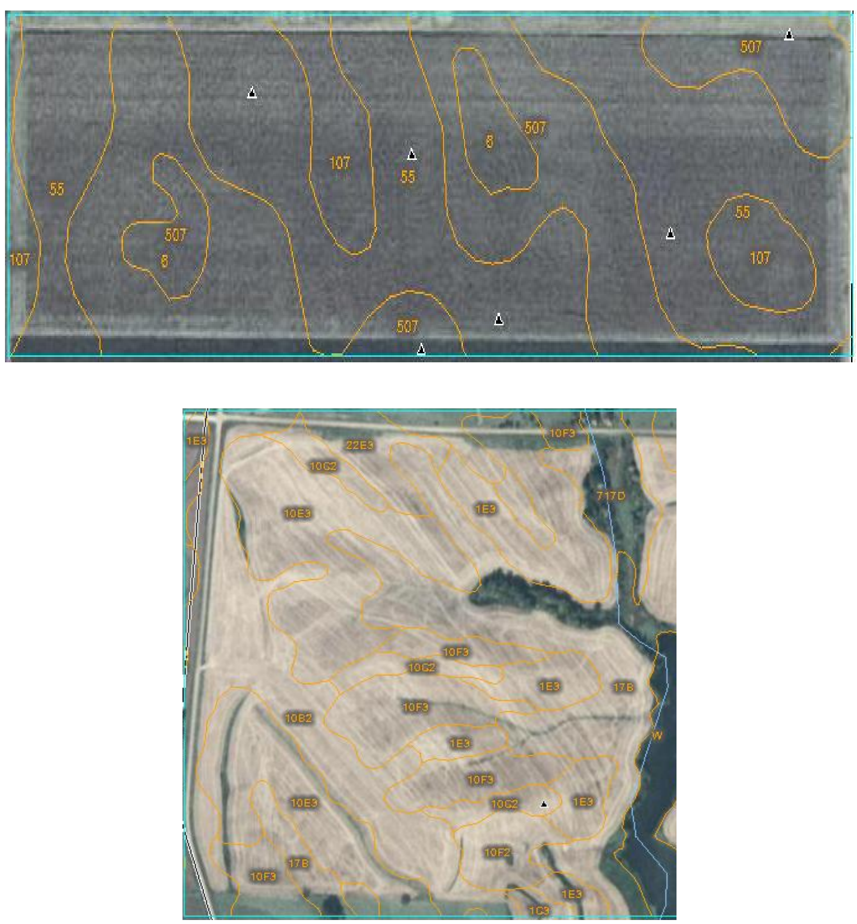

Figure 3. Soil survey maps of agricultural fields in Winnebago (top) and Crawford (bottom) counties, Iowa. These maps were downloaded from USDA-NRCS homepage (websoilsurvey.nrcs.usda.gov).

Table 3. Field boundaries for the two agricultural fields (Winnebago and Crawford counties, Iowa) used in the study.

Field	County	Corner	Latitude	Longitude
1	Winnebago	Southwest	43.260503	-93.881886
		Northeast	43.262456	-93.872101
2	Crawford	Southwest	41.957432	-95.562966
		Northeast	41.964771	-95.547173

This method of estimating tolerable biomass removal rates was simulated for six different geographic locations (defined by latitude and longitude) inside two agricultural fields in Winnebago and Crawford counties, Iowa (table 3, fig. 3). Slope, soil type, or both of these parameters were different in these six geographic locations. Slope values were 0.1% and 1.1% at the two locations in the Winnebago field, and slopes at the four locations in the Crawford field ranged from 2% to 13%. At each location, combinations of two tillage practices (conventional tillage and no-till) and two crop rotations (continuous crop corn and corn-soybean rotation) were considered, which gave a total of 24 different scenarios for biomass removal rate estimation (table 4). To estimate biomass removal rates in the soybean-corn rotation system, it was assumed that no biomass was collected during soybean harvesting season. The methodology was also used to develop a regularly gridded removal rate map for the field in Crawford county.

Results and Discussion

Agricultural biomass removal rates varied widely over the two agricultural fields in Iowa depending on crop management practices (tillage and rotation), field topography, and soil types (table 4, fig. 4). At the two locations in a relatively flat field in Winnebago county, 98% of the 11 Mg ha^{-1} (9900 lb ac^{-1}) total above-ground biomass was available for removal with negligible soil loss for both continuous corn and soybean-corn rotations. In estimating this removal rate, however, only the soil erosion tolerance threshold was considered as a constraint, and potential effects of excessive and continuous biomass removal on organic matter content and other biophysical soil properties were neglected.

No changes in biomass removal rates were observed with the changes in tillage practices and soil types at the two locations in the Winnebago field because soil loss in the field was always negligible and almost all of the above-ground biomass was removable. At these locations, soil types were Nicollet loam and Canisteo clay, respectively. The 2009 county-level average corn yield was 11.3 Mg ha^{-1}, and the soybean yield was 3.4 Mg ha^{-1} (USDA-NASS, 2010). These results are in agreement with the results of Newman et al. (2010) for similar field terrains, soil types, and management practices. Based on similar approaches using the RUSLE model and tolerable soil losses, other studies (e.g., Nelson, 2002; Johnson et al., 2006) have reported removal rates varying from 20% to 70%. However, these studies were based on countywide average slope values, which generally were higher than the slope of this field.

Table 4. Tolerable biomass removal rates at six different locations in two agricultural fields (Winnebago and Crawford counties, Iowa).

Location	Latitude, Longitude	Soil Type	Slope (%)	*T* Value (Mg ha^{-1} year^{-1})	Crop Rotation	Yield[a] (Mg ha^{-1})	Tillage	Biomass (Mg ha^{-1}) Total	Removable[b]
Field 1, Winnebago county									
1	43.261706, -93.873024	Nicollet loam	00.1	11.2	Corn	11.3	Conv.	11.1	10.9 (98%)
							No-till	11.1	10.9 (98%)
					Soybean/corn	3.4/11.3	Conv.	11.1	10.9 (98%)
							No-till	11.1	10.9 (98%)
2	43.262206, -93.872509	Canisteo clay	01.1	11.2	Corn	11.3	Conv.	11.1	10.9 (98%)
							No-till	11.1	10.9 (98%)
					Soybean/corn	3.4/11.3	Conv.	11.1	10.9 (98%)
							No-till	11.1	10.9 (98%)
Field 2, Crawford county									
1	41.961772, -95.562108	Monona silt loam	02.6	11.2	Corn	12.4	Conv.	12.3	12.1(98%)
							No-till	12.3	12.1 (98%)
					Soybean/corn	3.6/12.4	Conv.	12.3	12.1 (98%)
							No-till	12.3	12.1 (98%)
2	41.964085, -95.560799	Monona silt loam	07.5	11.2	Corn	12.4	Conv.	12.3	0
							No-till	12.3	10.8 (88%)
					Soybean/corn	3.6/12.4	Conv.	12.3	0
							No-till	12.3	9.6 (77%)
3	41.958852, -95.560777	Monona silt loam	12.6	9.0	Corn	12.4	Conv.	12.3	0
							No-till	12.3	8.6 (70%)
					Soybean/corn	3.6/12.4	Conv.	12.3	0
							No-till	12.3	7.0 (56%)
4	41.960320, -95.552065	Ida silt loam	12.8	9.0	Corn	12.4	Conv.	12.3	0
							No-till	12.3	9.2 (74%)
					Soybean/corn	3.6/12.4	Conv.	12.3	0
							No-till	12.3	8.4 (68%)

[a] Yield data were acquired from the USDA online resource (USDA-NASS, 2010).
[b] Only water-induced erosion was considered in the removable rate estimation.

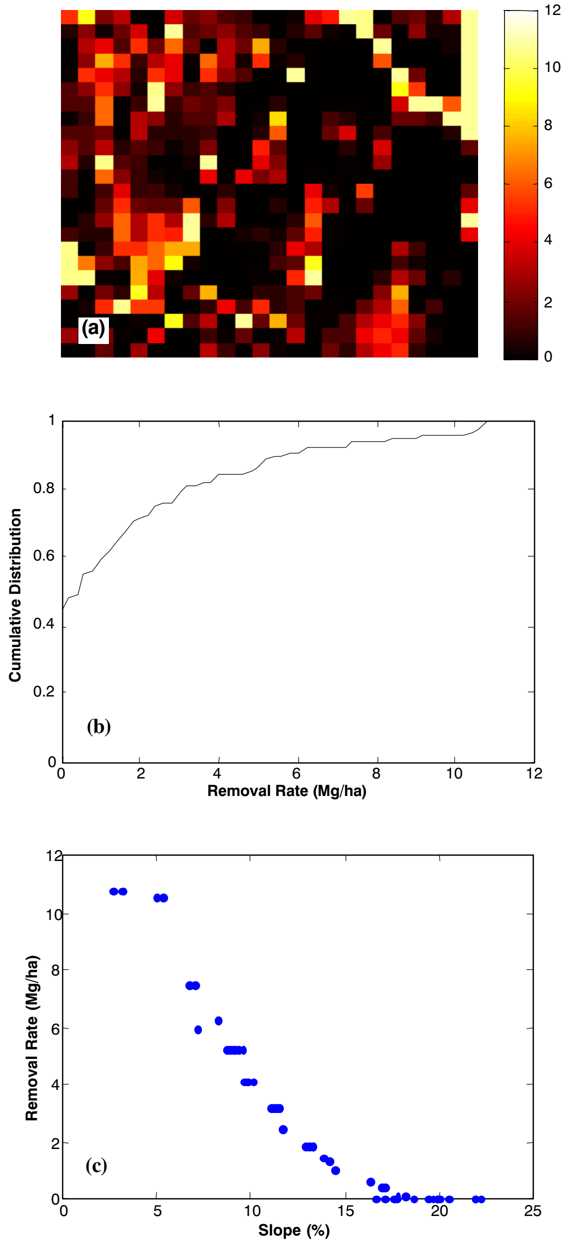

Figure 4. (a) Biomass removal rate map (Mg ha^{-1}) for a field in Crawford county, Iowa (fig. 3), (b) cumulative histogram of the removal rate map, and (c) removal rate as a function of slope. The map was developed for continuous corn, conventional tillage management. The relationship between removal rate and slope was developed for Napier silt loam soil.

At four geographic locations in the Crawford field with relatively uneven field terrain, the biomass removal rate decreased substantially as the slope increased from 2.6% to 7.5% and then to 12.6% with the same soil type, tillage practice, and crop rotation. At these locations, soil types were Monona silt loam (three locations) and Ida silt loam (one location). The 2009 average corn yield at these locations was 12.4 Mg ha^{-1}, and the soybean yield was 3.6 Mg ha^{-1} (USDA-NASS, 2010). At a location with a 2.6% slope, 98% of total above-ground biomass was available for removal under both conventional tillage and no-till practices when farmers were practicing a continuous corn rotation (table 4). However, no biomass was available for removal at locations with 7.5% and higher slopes when the farmers were using conventional tillage. If no-till practices were adapted, the removal rate went as high as 88% for the continuous corn rotation and 77% for the soybean-corn rotation at a location with a 7.5% slope. The interaction between tillage practices and biomass removal rates became more apparent with increasing slopes. As the intensity of tillage was reduced from conventional to no-till, the biomass removal rate increased, which is in agreement with the results from previous studies, including Nelson et al. (2004) and Wilson et al. (2004). At two locations with similar slope values, the biomass removal rates differed from one soil type to the other. For a no-till continuous corn management practice, the removal rate was 70% at a location with Monona silt loam and a 12.6% slope, whereas the removal rate was 74% at another location with Ida silt loam and similar slopes.

A lower level of tolerable biomass removal for conventional tillage was expected, as soil erosion will be more prevalent in tilled soil and additional surface cover is required to keep the soil loss below the tolerance level. No-till cropping practices with increased area of continuous corn production will be essential to increase the availability of biomass that can be removed safely. However, the literature showed that biomass removal will have a greater effect on soil loss than tillage practice (Lindstrom et al., 1979). Consequently, the benefit of no-till practices built into the RUSLE2 is partly the result of the high percentage of surface residue cover. In the event of a high percentage of biomass removal, the RUSLE2 will likely underestimate the soil loss; therefore, the tolerable biomass removal rate estimated using this method should be treated with sufficient care.

Lower levels of tolerable removal rates on steep slopes were also expected. In sloped terrain, higher levels of agricultural residue are required to minimize soil erosion, which leaves very little biomass to remove from the field. Generally, the actual yield in the sloped area will be lower than the county-level average yield used in this study. This discrepancy may lead to even less availability of removable biomass during actual field operations. On the other hand, single-pass biomass removal operations were mimicked using conventional multi-pass operations since the single-pass harvesting operations were not included in RUSLE2 database. This process of mimicking the single-pass harvesting operation means that there were more field operations in the simulation than in the intended single-pass harvesting operations in a field. Therefore, the simulation assumed more disturbances to the soil and higher soil loss for the given amount of biomass left in a field. Consequently, the simulation estimates lower removal rates than the actual available rates in the field for single-pass harvesting operations. The discrepancy will favor soil tilth, although it may not be substantial.

The RUSLE2 model showed that the soil loss from a field also depends on various supporting practices (Daniels et al., 2011). RUSLE2 showed that soil loss will decrease when new structures such as a silt barrier are added to a field. If soil loss decreases for a given amount of biomass removal, then more biomass, if available, can be removed before reaching the tolerable soil loss threshold. In this work, it was assumed that no supporting practices other than contour-following rows were used in the field. If farmers built supporting structures such as barriers and diversions, then water-induced soil erosion will decrease and the availability of removable biomass will likely increase.

Site-specific tolerable removal rates (Mg ha^{-1}) were also calculated in regular grids to create a removal rate map for the field in Crawford county (fig. 4a). This field was selected for the mapping because it has a wide variation in field terrain and soil types and provides a good opportunity for single-pass, variable-rate biomass collection. The map was developed for continuous corn, conventional tillage management with 35 m spatial resolution. The combination of corn-corn rotation with conventional tillage was selected in this study because this practice has been or is likely to be used widely in the corn growing regions of the U.S. In addition, a single-pass, variable-rate biomass collection system has a higher potential to be beneficial to the growers using such cultural practices. The tolerable removal rates varied from 0 to 12 Mg ha^{-1} over the field. This variation in the removal rates was caused by the changing field terrain in conjunction with the changing soil types. The field slope varied from 0% to approximately 25%, and the average slope length used was 45 m. An average slope length was used in this study to minimize the complexity and increase the computation speed of the system necessary to achieve real-time single-pass harvesting operations.

The removal rates were relatively higher in the northwest area of the field, where the slopes were relatively flat and the soil was less erodible. Essentially no biomass was available for removal in the east-central and southeast areas of the field. This result was expected, as these areas were characterized by very high slopes and highly erodible Monona/Ida silt loam soil. The linear pattern of the pixels in the northeast area, with higher removal rates, was formed over a ridge line of field terrain with a very small slope (fig. 4a). The histogram showed that about 45% of the field area had no or a negligible quantity of removable biomass, and about 3% of the area had biomass removal rates between 11 and 12 Mg ha^{-1} (fig. 4b). The removal rates changed substantially for small changes in slope when the slope was more than 5% for a given soil type (fig. 4c). This result indicates that the variable-rate removal will be useful when a field has slopes of about 5% or more. The total amount of biomass that can be removed from this field was estimated to be 67 Mg. The field had an average slope of 13.1%, and Napier silt loam was the soil type that covered the majority of the field. Based on these field averages, the total biomass available for removal was estimated to be 176 Mg. The higher biomass removal with field averages was expected, as substantial areas of the field were covered by relatively poor soil types, which was not captured in the field-average calculation that used Napier silt loam soil. This discrepancy also highlights the need for an in-field variable-rate removal estimation system for agricultural biomass.

These results indicate that there was a substantial variability in tolerable biomass removal rates within an agricultural field, and a site-specific variable-rate biomass collection system is essential to develop a sustainable biomass feedstock supply system. As discussed earlier, this study can be expanded to include the effect of wind erosion (when necessary) and the effect of continuous biomass removal on soil organic matter content and other biophysical properties to provide realistic recommendations for site-specific biomass removal rates. In a variable-rate single-pass crop grain and biomass harvesting system, these site-specific removal rates will be estimated during field operations and provided as a recommended rate to operators. Depending on the willingness of farmers, the capacity of harvesting and collection equipment, and market and weather conditions, biomass may be collected at lower rates than the recommended rates. Such single-pass operation requires real-time computation of the removal rates. Each iterative process of biomass removal rate estimation in this study took an average of about 2 s on a desktop computer with a Pentium 4 microprocessor running at 2.4 GHz with 1 GB RAM. For a DEM resolution of 10 m, this simulation speed will be sufficient to provide real-time estimation for single-pass harvesting ground speeds at or below 5.0 m s^{-1}. Faster simulation speed is possible with the use of currently available multicore processors.

Conclusions

A methodology was developed for variability analysis and site-specific estimation of tolerable agricultural biomass removal rates for single-pass crop grain and biomass harvesting systems. The methodology was used to estimate biomass removal rates in two different agricultural fields in Iowa. It can be concluded from this study that tolerable biomass removal rates vary substantially over different locations in a field depending on field terrains, crop management practices, and soil types. At a location in a field in Winnebago county, Iowa, with ~1% slope and conventional tillage practices, up to 98% of 11 Mg ha^{-1} total above-ground biomass was available for collection with negligible soil loss. In contrast, there was no above-ground biomass available for collection at a location in Crawford county, Iowa, with a 12.6% slope and conventional tillage practices. If no-till practices were adopted, up to 70% of the biomass could be collected from the same location. In the case of a soybean-corn rotation with no-till practices, about 98% of the above-ground biomass was available for removal at the locations with small slope values in the Winnebago field, whereas about 56% of the biomass was available at a location in the Crawford field with a 12.6% slope. The removal rate map developed in this study also showed a substantial variation in biomass removal rates over an agricultural field, which showed the importance of in-field, site-specific removal rate estimation. The biomass removal rates estimated in this work will be useful in providing a recommended value for the farmers to set a biomass removal level during single-pass crop grain and biomass harvesting operations. However, this study only considered the soil erosion tolerance level in estimating biomass removal rates. Before providing the final recommendation to end users, further investigations will be necessary to study potential effects of continuous biomass removal on organic matter content and other biophysical soil properties. This type of site-specific biomass removal rate estimation is necessary to achieve field-level sustainability in agricultural biomass production and collection systems.

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